PHILOSOPHICAL
TRANSACTIONS A

Phil. Trans. R. Soc. A.
doi:10.1098/not yet assigned

1 – 1 = Counterfactual: On the Potency and Significance of Quantum Non-Events

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Keywords: Quantum oblivion, nonevents, IFM, time-symmetry

Summary

We study the unique role played by nonevents in quantum mechanics. Our earlier analysis of the "quantum oblivion effect" has revealed some subtle stages in the measurement process, which sometimes end up in self-cancellation. To these findings, we now add two insights derived by two time-symmetric interpretations of QM. If the nonevent, like all quantum interactions, is formed by the conjunction of forward-plus-backward-evolving wavefunctions, then it is another feature of such dual processes, namely the involvement of negative masses and energies, that enables Nature to make some events "unhappen" even after leaving causal traces.

Main Text

So many, varied, and sharp are the differences between quantum and classical physics; so persistent the conflicts between the quantum formalism's predictions and macroscopic reality; and so unsatisfactory have all proposed resolutions remained so far; that it is not unlikely that all these quantum oddities share a more basic common origin. Should that be the case, novel "method in the madness" may emerge, offering hints for the long sought-for theory that would more naturally account for these and other oddities.
This is the aim of the present paper. We submit that

i) A promising candidate for a "master quantum oddity" is the unique status of the *nonevent*, namely, an event which *could have happened but did not*. This said, QM immediately turns out to be unique in that a nonevent within its realm can exert significant causal effects just by virtue of this "could have."

ii) Earlier [1, 2], studying apparent violations of momentum conservation in very basic quantum interactions, we have shown that, upon finer time resolution, momenta have been exchanged, yet recurrent exchanges ended up in a net zero result. We proposed the term "Quantum Oblivion" for these self-canceling interactions.

iii) Another piece of the puzzle may come from some time-symmetric interpretations of QM, according to which the quantum interaction is formed by *two* time evolutions, going back and forth between past and future.

iv) Significantly, these time-symmetric models, for their own reasons, have also invoked *negative values, such as mass and energy, are also exchanged between past and future events*.

v) The emerging account is therefore very intuitive. *Both positive and negative values, such as mass and energy, are exchanged between past and future events*. These give rise to the familiar quantum nonlocal and nontemporal phenomena, which, *despite apparent violations of space and time limits, obey conservation laws and the non-signaling principle.*

vi) Quantum oblivion is thus rendered as an event which, in some deeper sense, has occurred and then "unoccurred."

vii) Bearing in mind that *quantum nonevents far outnumber events in our universe*, several foundational issues in classical physics may get new twists.

This general model has been named "quantum hesitation" [2] honoring L. de-Broglie's quantum-mechanical rephrasing of Bergson's definition of time as Nature's hesitation between possible outcomes.

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1. The Nonevent

Consider an isolated atom somewhere in empty space, absorbing a photon at time t_1 and thereby becoming excited. It remains in this state until it re-emits the photon, which at a later time t_2 is absorbed by a distant macroscopic system. By irreversibly amplifying the absorption event, that system functions as a detector. Assume further that this detector can also record the absorption's time with considerable accuracy.
Apparently, the detector has recorded a single event, namely the photon's absorption. Little reflection, however, makes it clear that *numerous events have occurred prior to* t_2. Every instance in which the detector remained silent is also a quantum event. Moreover, bearing in mind countless other distant systems in the universe which could have acted as potential detectors makes the number of events much greater.
This is by no means a mere philosophical assertion. A plethora of elusive phenomena can be revealed by studying quantum nonevents in experiment and theory.

1.1. The Information Conveyed between Feynman's Irregular Clicks

Richard Feynman's reputation as a genius physicist was matched by his reputation as an inspiring teacher. It was he who famously argued that the double-slit experiment presents the core mystery of quantum mechanics. His classic lecture on this topic employs a stream of single electrons undergoing interference, with two sensitive detectors, each placed next to one of the slits, to indicate which path the electron has taken. His vivid style is best quoted verbatim:
The first thing we notice with our electron experiment is that we hear sharp "clicks" from the detector (that is, from the loudspeaker). And all "clicks" are the same. There are no "half-clicks."
We would also notice that the "clicks" come very erratically. Something like: click ….. click-click … click …….. click …. click-click …… click …, etc., just as you have, no doubt, heard a Geiger counter operating. If we count the clicks which arrive in a sufficiently long time – say for many minutes – and then count again for another equal period, we find that the two numbers are very nearly the same. So we can speak of the average rate at which the clicks are heard (so-and-so-many clicks per minute on the average) [3].
These clicks are, by nature, indeterministic. But is this the only indeterminacy? What about the intermediate silences, the *non-clicks*? This is Interaction-Free Measurement [4], which demonstrates the causal efficacy of quantum nonevents: Omit one detector, and, lo and behold, interference would vanish exactly as before! These non-clicks turn out to contain a significant amount of quantum information.
Nonevents, then, not only far outnumber the events in our universe, they take a major causal portion in every physical process.

1.2. Isolating the Nonevent

Einstein's advice "Make things as simple as possible, but not simpler" may offer further help. The following experiment provides the simplest quantum interaction that can shed new light on the nature of nonevents.

Consider an electron and a positron, both with spin state $\left|z_+\right\rangle = \frac{1}{\sqrt{2}}(\left|x_+\right\rangle + \left|x_-\right\rangle)$ and momenta $(p_x)_{e^-} < (p_x)_{e^+}$, $(p_y)_{e^-} = (p_y)_{e^+}$, entering two Stern-Gerlach magnets positioned at (t_0, x_{e^-}, y_0) and (t_0, x_{e^+}, y_0), respectively (Fig. 1). The magnets split the particles' paths according to their spins in the *x* direction:

$$\left|\psi_{e^-}\right\rangle = \frac{1}{\sqrt{2}}(\left|1'_{e^-}\right\rangle + \left|1''_{e^-}\right\rangle) \text{ and } \left|\psi_{e^+}\right\rangle = \frac{1}{\sqrt{2}}(\left|2'_{e^+}\right\rangle + \left|2''_{e^+}\right\rangle). \quad (1)$$

Let care be taken to ensure that, should the particles turn out to reside in the intersecting paths, they would mutually annihilate.
Let us follow the time evolution of these two wave-functions plus two nearby detectors $\left|READY\right\rangle_1$, $\left|READY\right\rangle_2$, set to measure the photon emitted upon pair annihilation, which would change their states to $\left|CLICK\right\rangle_1$ or $\left|CLICK\right\rangle_2$.
Initially, the total wave-function is the separable state:

$$\left|\psi\right\rangle = \frac{1}{2}(\left|1'_{e^-}\right\rangle + \left|1''_{e^-}\right\rangle)(\left|2'_{e^+}\right\rangle + \left|2''_{e^+}\right\rangle)\left|READY\right\rangle_1\left|READY\right\rangle_2. \quad (2)$$

The particles, depending on their positions at t_1 or t_2, may (not) annihilate and consequently (not) release a pair of photons, which would in turn (not) trigger one of the detectors.
At $t_0 \leq t < t_1$, then, the superposition is still as in Eq. 2. But at $t_1 < t < t2$, either a photon pair is emitted, indicating that the system ended up in $\left|1''_{e^-}\right\rangle\left|2'_{e^+}\right\rangle\left|CLICK\right\rangle_1\left|READY\right\rangle_2$, *or not*, thereby

$$\left|\psi\right\rangle = \frac{1}{\sqrt{3}}[(\left|1'_{e^-}\right\rangle + \left|1''_{e^-}\right\rangle)\left|2''_{e^+}\right\rangle + \left|1'_{e^-}\right\rangle\left|2'_{e^+}\right\rangle]\left|READY\right\rangle_1\left|READY\right\rangle_2, \quad (3)$$

which is a superposition of an interesting type: one component of it is a definite state, as usual, while the other is a superposition in itself.

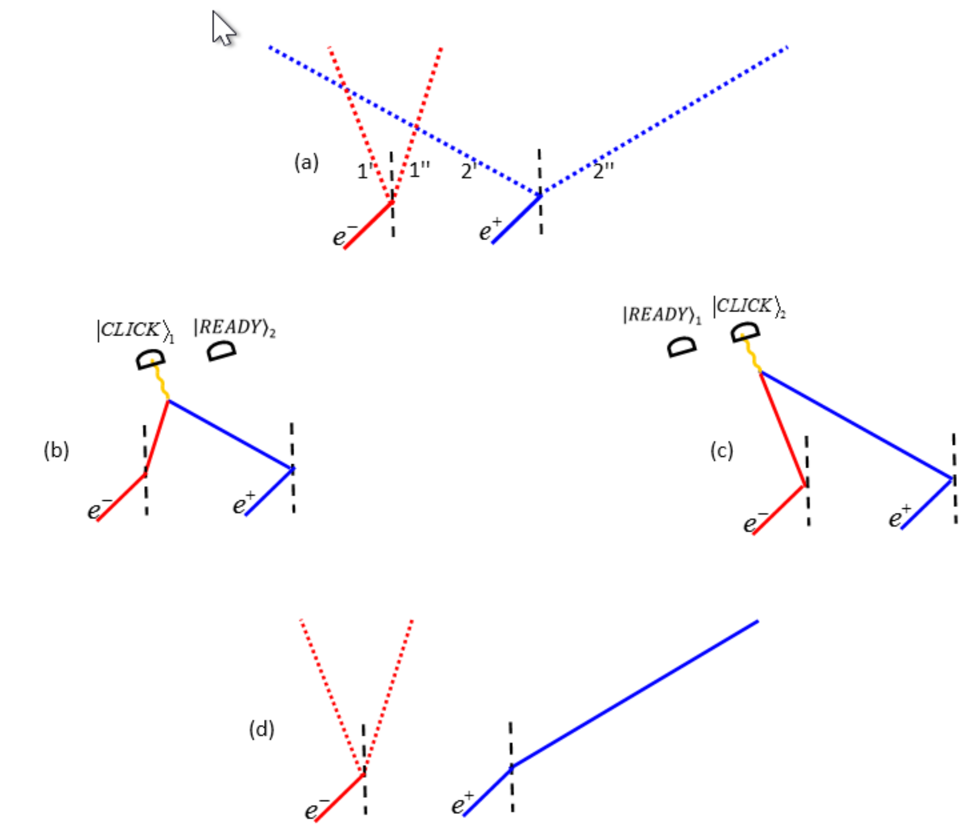

Fig. 1: Possible electron-positron interactions and its possible outcomes. (a) The setting. (b-c) Annihilation. (d) Oblivion.

Similarly at $t > t_2$: If a photon pair is emitted, we know that the particles ended up in paths 1' and 2': $\left|1'_{e^-}\right\rangle\left|2'_{e^+}\right\rangle\left|READY\right\rangle_1\left|CLICK\right\rangle_2$. Otherwise, however, we find the product state:

$$\left|\psi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|1'_{e^-}\right\rangle + \left|1''_{e^-}\right\rangle\right)\left|2''_{e^+}\right\rangle\left|READY\right\rangle_1\left|READY\right\rangle_2, \tag{4}$$

which is peculiar. The positron is observably affected: If we time-reverse its splitting, it may fail to return to its source. Its momentum has thus changed. Not so with the electron: It remains superposed, hence its time-reversibility remains intact (Fig. 2).

Summarizing, this is Quantum Oblivion (QO), where one party of the interaction “remembers” it through momentum change, while the other remains unaffected, apparently violating momentum conservation.

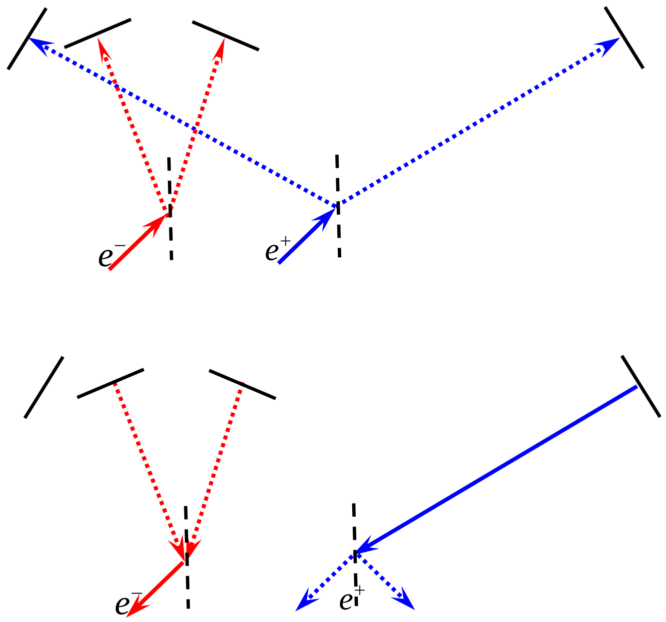

Fig. 2: The peculiar momentum exchange due to outcome (d) in Fig. 1: The positron's interference is changed while that of the electron remains intact.

1.3. The Critical Interval: The Nonevent was not that Silent After All

It is obviously the intermediate time-interval $t_1 < t < t_2$ that conceals the momentum conservation in QO. The details, however, are no less interesting.

The two particles, during this interval, become partly entangled in both their positions and momenta. Suppose, *e.g.*, that within the interval we reunite the two halves of each particle's wave-function through the original BS, to see whether they return to their source. *Either one* of the particles may fail to do that, in which case the other must *not*. Similarly for their positions. This is *entanglement*, identical to that of the electron-positron pair in Hardy's experiment [5]:

$$|\psi\rangle = \frac{1}{\sqrt{3}}[(|1'_{e^-}\rangle + |1''_{e^-}\rangle)|2''_{e^+}\rangle + |1'_{e^-}\rangle|2'_{e^+}\rangle] \; . \tag{5}$$

The state during this interval is a *higher-order superposition*: It is an entangled state, composed of a superposed and a non-superposed state.

Equally interesting is the partial entanglement manifested by this state, the outcome of which is *un*entanglement. This term is proposed instead of the familiar "*dis*entanglement," in order to capture the event's uniqueness. Whereas disentanglement presents the direct consequences of entanglement, *e.g.*, the EPR correlations following spin measurements, unentanglement is a process that gives the deceptive impression that entanglement *never took place*. Rephrased in more familiar terms, the wave-function undergoes momentary decoherence followed by "*re*coherence." Notice that, in contrast to the familiar decoherence induced by the macroscopic environment, which is usually believed to be irreversible, here it temporarily ensues by the interaction's mere *potential* to become macroscopic.

1.4. Oblivion's Ubiquity: Every Detector's Pointer must be Superposed in the Conjugate Variable

We now submit our main argument. Rather than a curious effect of a specific interaction, *Oblivion is part and parcel of every routine quantum measurement*. Its elucidation can therefore shed new light on the nature of measurement, further enabling some novel varieties of it.

Ordinary quantum measurement requires a basic preparation often considered trivial. Consider *e.g.,* a particle undergoing position measurement (also employed during standard spin measurements). The detector's pointer, positioned at a specific location, reveals the particle's presence in that location by receiving momentum from it. This requires, by definition, that the pointer will have rather precise momentum (preferably 0). In return, however, the pointer's position must be highly *uncertain*.

Let this tradeoff be illustrated by our first experiment (Fig. 1) with one modification. In the original version, the experiment's two possible interactions are annihilations, which are mutually exclusive. Let us replace annihilation by mere collision (Fig. 3): Simply, let two superposed atoms *A1* and *A2* interact exactly like the electron and positron in Fig. 1. Instead of annihilating, then, they merely collide, which can now happen on *both* possible occasions at t_1 and t_2, namely at the two locations where A2 can reside. This experiment's outcome is more interesting. Suppose that the detector on path 2" (positioned closer to the beam-splitter, see Fig. 3b) remains silent: We know that the two atoms have collided, but remain oblivious about this collision's location. What we thus measure is ordinary momentum exchange: Both atoms' momenta have been reversed along the horizontal axis. Here, oblivion is negligible, affecting only the two atoms' positions. Yet, because A2 has vanished from the macroscopically distant location on 2", the final outcome is a position measurement of A2.

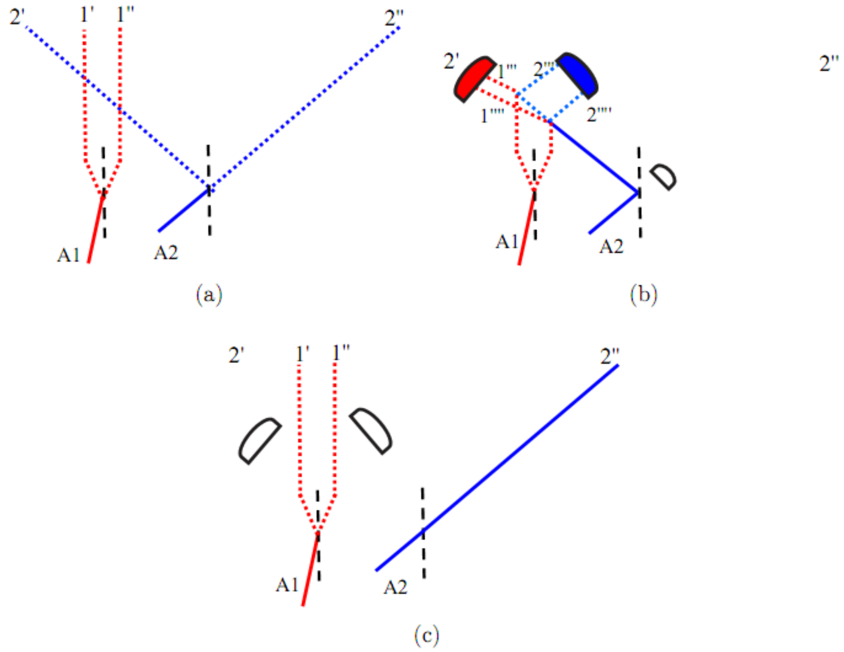

Fig. 3. Same interaction as in Fig. 1 but with two atoms that do not annihilate upon interaction but (a) merely form elastic collision. In this version, the critical interval is the detector's long exposure time which does not allow the precise detection time. (b) Measurement ending up with collision, where the nearby detectors' widths signify that A1's and A2's positions remain superposed. (c) IFM.

Conversely, we may fail to detect A1 and A2 in paths 1''' 1'''' and 2''' 2'''', to which they would be diverted in case of collision. We are now certain that A2 resides on path 2" while A1 has returned to its initial superposition over 1' and 1" (Fig. 3c). In other words, A2 undergoes momentum oblivion, which is again an ordinary position measurement of A1, but this time the measurement is *interaction-free* – a point studied in greater detail below.

To summarize: We have studied an asymmetric interaction between two atoms, where two halves of A1's wave-function interact with one half of A2, under great time- and position resolution. Two momentum exchanges can occur between the two atoms:

- *i)* A2 turns out to have collided with A1. This amounts to A2 undergoing position measurement. The price exacted by the uncertainty principle is a minor position oblivion of both A1 and A2.
- *ii)* A2 turns out to have *not* collided with A1. This again amounts to A2 undergoing position measurement – collapsing it to the remote 2" path. Here, however, a macroscopic momentum oblivion plagues A1, making the measurement interaction-free.

Both (*i*) and (*ii*) occur under an unusually great space- and time-resolution, enabling a novel study of the Critical Interval. During this interval, entanglement between the two atoms has ensued, as they have assumed new possible locations

$$\left|\psi\right\rangle = \frac{1}{2}[\left|1'''\right\rangle\left|2''''\right\rangle + \left|1''''\right\rangle\left|2'''\right\rangle + (\left|1'''\right\rangle + \left|1''''\right\rangle)\left|2''\right\rangle], \qquad (6)$$

which has remained undistinguished until the macroscopic detection which finalized the interaction and sealed the oblivion.

The generalization is natural. During *every* quantum measurement, the detector's pointer interacts with a particle in the same asymmetric manner as atoms 1 and 2: The particle's wave-function's *part* interacts with the pointer's wave-function's *whole*. To make the analogy complete, recall that in reality the pointer's superposition is continuous rather than discrete. As the pointer thus resides over a wide array of locations, momentum measurement becomes much more precise. This passage from discrete to continuous superposition also opens the door for several interesting interventions [1, 2].

2. The Clue of Escher's Self-Drawing Hands: Use Time to Bypass Spatial Restrictions

The above account of quantum oblivion is a purely orthodox one, based on standard quantum theory alone. It thus says nothing about the process by which the decision is made which of all possible interactions between the particle and the pointer will eventually be materialized, leading to the extinction of all its competitors. Such an explanation lies, of course, outside of quantum formalism, which is the very reason for the development of several interpretations of QM. In our case, it turns out that two of the most radical interpretations offer the best clues for a deeper account of quantum measurement in general and oblivion in particular.

M. C. Escher has earned his reputation by numerous paintings that portray impossible causal loops, such as a pair of hands drawing one another, or a waterfall where water falling downwards still close into an eternal circle, *etc*. These pictures do not challenge our physical intuition because we know that the artist has employed normal causality to create the paradoxical causal chain. In other words, *the apparently consecutive stages that we see in the picture were drawn in a different order in time*.

Is it possible that the causal anomalies manifested by quantum uncertainty and non-locality owe their existence to a somewhat similar creation? This is the spirit of the Time-symmetric interpretations considered below.

2.1. The Transactional Interpretation: Each Quantum Interaction is Affected by the Past as well as the Future

Following is a brief introduction of Cramer's transactional interpretation of quantum mechanics [6]. Any quantum event that involves the exchange of conserved quantities (energy, momentum, angular momentum, etc.), and that can be represented by a matrix element, is considered to have been formed in three stages:

1. An "offer wave" (the usual retarded wave function $\psi(x)$ or a ket $|\psi\rangle$) originates from the "source" (the object supplying the quantities transferred) and spreads through space-time until it encounters the "absorber" (the object receiving the conserved quantities).
2. The absorber responds by producing an advanced "confirmation wave" (the complex conjugate wave function $\psi^*(x)$ or a bra $\langle\psi|$) which travels in the reverse time direction back to the source, giving rise to the density $\psi^*\psi$.
3. The source chooses between the possible transactions $\{i\}$ based on the strengths of the $\psi_i^*\psi_i$ echoes it receives, and reinforces the selected transaction repeatedly until the conserved quantities are transferred and the potential quantum event becomes real.

It is quantum non-locality where the transactional interpretation offers its best reward. Basically, it takes advantage of the trivial effect that the two entangled systems, though spacelike-separated, have been *locally* connected in the past. The quantum transaction, along the resulting spacetime zigzag, makes the effect much more natural, as can be seen in Cramer's own illustration (Fig. 4)

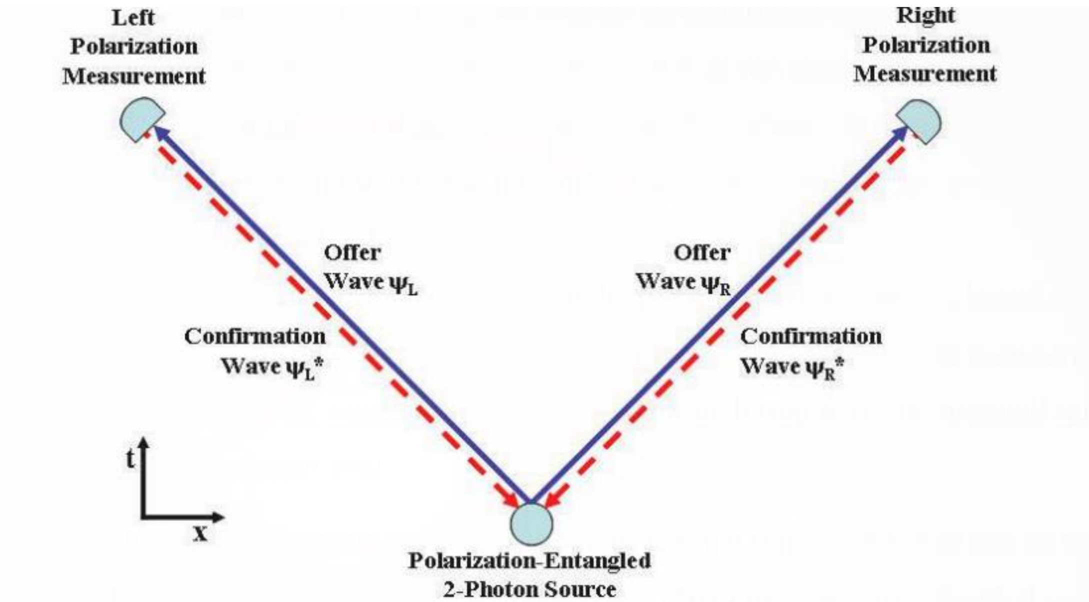

Fig. 4: Transactions between past and future events in an EPR experiment.

2.2. The Two-State-Vector Formalism: The Combined Causal Effect of Past and Future States Can Yield Odd Values

Despite several important differences, the basic, time-symmetric idea of TI appears in Aharonov's Two State-Vector Formalism (TSVF) which originates from the work of Aharonov, Bergman and Lebowitz [7]. It asserts that every quantum system is determined by two wave-functions: One (also known as the pre-selected wave-function) evolves forward in time while the other (post-selected) evolves backward. The forward- and backward-evolving wave-functions, $|\psi_i\rangle$ and $\langle\psi_f|$, respectively, define the so called two-state vector $\langle\psi_f| \quad |\psi_i\rangle$. The two wave-functions are equally important for describing the present of the quantum system via the weak value of any operator A defined by

$$\langle A\rangle_w = \frac{\langle\psi_f|A|\psi_i\rangle}{\langle\psi_f|\psi_i\rangle} \qquad (7)$$

Here a logical catch ensues: "The state between two measurements" cannot be revealed by measurement.
Weak measurement [8, 9] was conceived in order to bypass this obstacle as well as to test other TSVF's predictions. This led to numerous intriguing works, both theoretical and experimental.

2.3. Why Time-Symmetric Causality?

Our reasons for opting for the time-symmetric interpretations of QM have been explained in several earlier works. Although their picture of quantum reality is not complete, at times even opening new questions, they offer very elegant explanations for well-known quantum paradoxes, as well as some novel ones revealed in earlier works of ours [10]. Such is the present case. Our analysis of quantum oblivion has revealed intermediate stages occurring during the formation of the quantum nonevent, hence the intriguing causal efficacy of IFM. *The interaction between the quantum and the macroscopic pointer turns out to consist of a feeble occurrence of the event, followed by its "unoccurrence."* It is therefore only natural to ask whether these stages occur during the back-and-forth exchanges between future and past, invoked by these bold models.

3. The Complementary Clue: Erasure must be Added for Making the Deception Perfect

But it was not only for its elegance that we have found time-symmetric quantum causality to naturally integrate with our findings. Both TI and TSVF, for their own reasons, had to invoke negative values like negative energy and negative momentum as part of their mutual interactions along both time directions. Which bring us back to the visual analogy we employed earlier: When Escher was drawing his masterpieces, he was not only going back-and-forth in terms of the paradoxical causality he was presenting; without doubt, he also used a great deal of erasure in the process. With the appropriate caution needed when following analogies, let us follow this one as well.

3.1. Negative Energy Exchange in TI

Creamer drew his initial inspiration from the Wheeler Feynman "absorber theory" of electromagnetism. They invoked retarded and advanced waves going between source and the absorber, such that, due to destructive interference, all the intermediate anomalies of advanced waves eventually disappear. Creamer found it natural to follow this reasoning into the quantum realm:
The emitter can be considered to produce an "offer" wave F1 which travels to the absorber. The absorber then returns a "confirmation" wave to the emitter and the transaction is completed with a "handshake" across space-time. To an observer who had not viewed the process in the pseudo-time sequence employed in the above discussion, there is no radiation before T1 or after T2 but a wave travelling from emitter to absorber. This wave can be reinterpreted as a purely retarded wave because its advanced component G2, a negative energy wave travelling backwards in time from absorber to emitter, can be reinterpreted as a positive energy wave travelling forward in time from emitter to absorber, in one-to-one correspondence with the usual description.
Thus the W-F time symmetric description of electrodynamic processes is completely equivalent in all observables to the conventional electrodynamic description. Time-symmetric electrodynamics, in both its classical and quantum mechanical forms, leads to predictions identical with those of conventional electrodynamics [6, p. 669].

3.2. Weak Quantum Values can be Odd, even Negative

Next comes what may be TSVF's most intriguing prediction. Consider the values straightforwardly predicted for mass and momentum in the following experiment.
The Three Boxes Paradox [11] is a by-now familiar surprise yielded by TSVF. A particle is prepared with equal probability to reside in one out of three boxes:
$|\psi_i\rangle = \frac{1}{\sqrt{3}}(|1\rangle + |2\rangle + |3\rangle)$.
Later it is post-selected in the state
$|\psi_i\rangle = \frac{1}{\sqrt{3}}(|1\rangle + |2\rangle - |3\rangle)$.

What is the particle's state between these two strong measurements? By definition, *projective measurement is unsuitable for answering this question*, as it reveals the state *upon* the intermediate measurement. It is *weak* measurement, again, that comes to help. TSVF predicts the following weak values of the projection operators, $Pi \equiv |i\rangle \langle i|, for\ i = 1,2,3$:

$$\langle P_1 \rangle_w = 1$$
$$\langle P_2 \rangle_w = 1$$
$$\langle P_3 \rangle_w = -1$$

Therefore, the total number of particles is *1*, as should be, but it is a sum of two ordinary particles plus one odd. That is, the first two boxes contain a particle with certainty, while the third box contains a particle with an apparent "negative probability." Can this odd mathematical value be given physical meaning? If we choose to trust the formalism, we can assign the negative value to mass.

The last equation denotes negative weak value for the very existence in the third box. In order to fully grasp the paradoxical nature of this term, let us consider within the context of its standard versions:

If "probability *1*" means "The particle certainly resides within this box";
and "probability *0*" means "The particle has never resided within this box";
then "probability *-1*" means "The particle certainly *un*resides within this box."

As absurd as third expression may sound, this is its simplest non-mathematical meaning, the alternative being dismissing it as meaningless. The choice to trust the mathematics, has led to assigning a negative sign to every interaction involving the third box, as long as it is weak enough. Obviously, this cannot be related to the particle's charge, as it played no role from the beginning. The remaining choice is mass. The simplest way to prove this prediction is through the particle's momentum: A collision with another particle must give the latter a "pull" rather than a "push," even though their initial velocities were opposite. Moreover, since weak values are additive, if one is interested to know, for instance, what is the net interaction with the second and third boxes, he will find the 1-1=0 net interaction which motivated the title of this paper. Can this prediction be put to test? A preliminary version has already yielded promising results [12].

In passing, it is worth comparing this step of the TSVF to Dirac's choice to trust the mathematics upon encountering the negative value for the electron's charge, following the dual solution for his famous equation. That choice has later led to the discovery of the positron. This may be the case with the present choice as well.

3.3. Weak, Odd and Negative – but not Necessarily Rare

To the extent that the above weak values are indeed part of quantum reality rather than a mere mathematical curiosity, one cannot help asking whether their existence is limited to the probabilistic fringe that allows them, namely, under very unique pre- and post-selections. If we do not observe such values under "ordinary" quantum interactions, that may be because they do not exist there, but there is also another possibility which merits consideration:

Is it possible that even a normal quantum value is the sum of several odd quantum values? Should that be the case, a fairly simple spatiotemporal evolution may underlie the unique quantum phenomenon which we seek to explain, namely the nonevent.

We are well aware of the extent of speculation in which we indulge towards the end of this work. Not only do we favor the highly unorthodox account of time symmetric quantum causality, but we are willing to ascribe it exchanges of negative momentum and mass to account for the fact that, despite its spatial and temporal oddities, the quantum interaction does obey conservation laws.

4. From Information to Ontology

How, then, can non-events play part in the quantum process? The challenge's acuity is reflected in the various radical moves it has elicited from the reveal interpretations of QM, of which two famous schools have desperately resort to the extreme opposites:

i. *Abandonment of ontology: Copenhagen*. Since counterfactuals are facts of our knowledge, just like actual facts, let us define QM as dealing only with knowledge, information, *etc*., rather than with objective reality.

ii. *Excess ontology: Many worlds*. The counterfactual does occur, but in a different world, split from ours at the instant of measurement.

Our own option is in the spirit of Wigner in his celebrated essay "The unreasonable effectiveness of mathematics in the natural sciences" [13]. Information, especially in its mathematical version, under appropriate manipulation of its own symbols, yields additional, underlying non-information that may sometimes strike us as surprising or even wrong, yet if we take it seriously, we may find that Nature indeed possesses the properties which this new information has conveyed the earlier. Wigner, following a long line of thinkers ever since Plato, mused that "The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve." We dare not go into these profound philosophical issues, yet we find that in the case of quantum nonevents, this approach offers, paradoxically, a *demystifying* account of the quantum world.

5. Summary

We now return to the question posed at the beginning of this article: How can a quantum event which has never occurred, only could have occurred, exert observable causal effects? Our analysis of quantum oblivion has straightforwardly revealed some very elusive intermediate stages in the formation of the measurement event, which can sometimes end up

in nearly perfect self-cancellation, yet living some traces in neighboring systems. We then found it natural to follow the Transactional Interpretation and the Two State-Vector Formalism of quantum mechanics in search of a more comprehensive account of this process. Several insights emerging from these works, and moreover some experimental predictions of the TSVF, converged into a picture in which advanced and retarded actions equally take part in the formation of the quantum event, where even physical values known so far to be only positive, like energy and mass, can also change their sign.
Whether the luring analogies which have guided us were genuine, the burden of proof remains with us, to be addressed in works to follow.

Acknowledgements
We are grateful to Yakir Aharonov for many inspiring discussion. E.C. acknowledges support from ERC AdG NLST.

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